



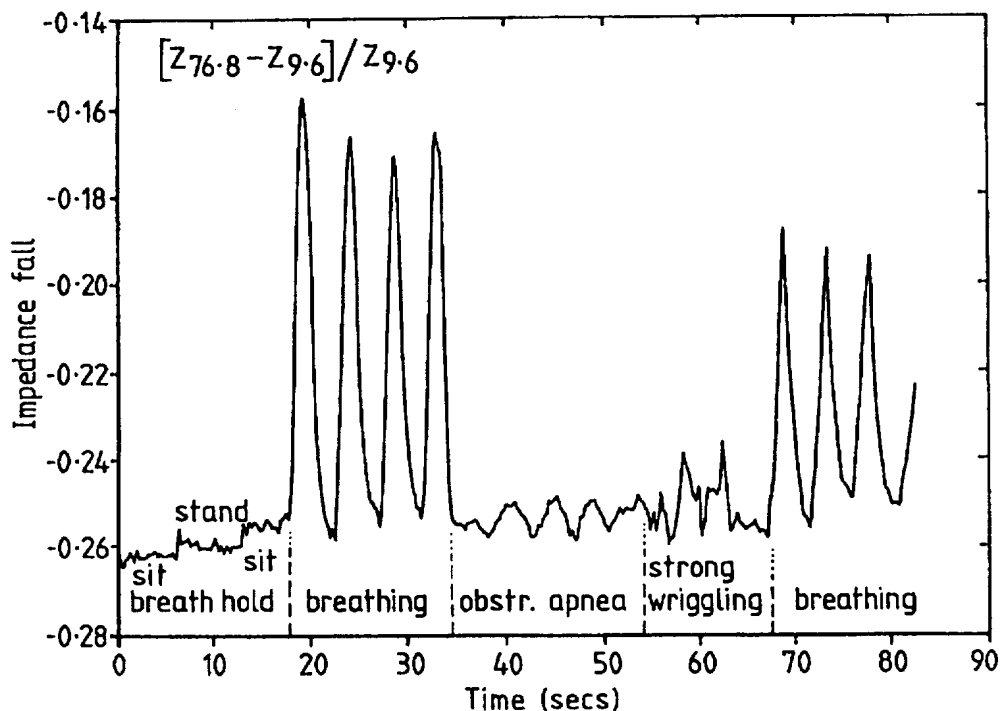
## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(54) Title: IMPEDANCE PNEUMOGRAPHY

## (57) Abstract

The invention concerns a method and apparatus for monitoring respiratory condition by impedance pneumography. An electrical signal is applied at a plurality of frequencies to a human subject by way of a first pair of spaced electrodes applied to the trunk of the body, whilst the resulting electrical signal is monitored at said plurality of frequencies at different points on the body by way of a second pair of spaced electrodes. From the resulting electrical signal a measure of the impedance of a part of the body at the plurality of frequencies is obtained, and a difference signal representing the impedance change with frequency is calculated. The difference signal is normalised with respect to a signal representative of the impedance measure itself at one or more frequencies, thereby suppressing the effect of those impedance signal components -such as movement artefact- whose frequency dependent change is substantially proportional to the impedance signal value. The invention improves the reliability of impedance pneumography, especially when employed in situations in which it is difficult to restrict subject movement, such as during sleep. It has particular application in neonatal and infant sleep apnoea detection systems.



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## Impedance Pneumography

The present invention relates to impedance pneumography and, more specifically, to a method and apparatus for monitoring respiratory condition by impedance pneumography.

5        Impedance pneumography is a known technique of ventilation monitoring, involving the measurement of respiration from electrical impedance changes in the chest. Many investigations have confirmed the high correlation between impedance change and volume of air breathed, whilst the simplicity of this method of respiratory monitoring makes it a very attractive technique as direct contact with the airstream is not required. In  
10       practice, the technique is carried out by placing two or four ECG electrodes on the chest wall, and both the electrocardiogram and impedance pneumogram may be recorded from the same electrode set.

      Impedance changes, particularly in the chest, are a complex function of geometry and conductivity and many studies have been undertaken in an attempt to understand the  
15       relationship between impedance changes and specific physiological changes. In conventional impedance pneumography, little current passes through the lung tissue itself and it is the current passing through the subject's chest and back that contributes most to the impedance change. This is one of the reasons why movement artefact in the resulting pneumogram may be very significant, and in measurements where it is difficult to restrict  
20       movement, conventional pneuemographic monitoring can be highly unreliable. In a particular and important application, sleep apnoea detection systems using impedance pneumography techniques give very unsatisfactory results, due to the sensitivity to body movement. Changes in body shape and/or in the skin-to-electrode impedance can produce large amplitude artefacts, in many cases larger than the respiratory signal itself. In neonates  
25       and infants especially, the impedance fluctuations caused by cardiac activity can be misclassified as breathing, which might falsely prevent an alarm if obstructive apnoea occurs.

      A recent investigation into transthoracic impedance, "Signal-to-Motion Artefact Ratio Versus Frequency for Impedance Pneumography", Rosell & Webster, IEEE  
30       Transactions on Biomedical Engineering, Vol. 42, No. 3, March 1995, pages 321-323,

demonstrated the frequency-dependent aspects of pneumograph measurements. The study described concluded that working at higher frequencies improves the signal-to-motion artefact ratio and suggested a method to further increase this ratio. Development of this study has led to the design and testing of an adaptive filter to increase the signal-to-motion  
5 artefact ratio ("Reduction of Motion Artefact Using a Two-Frequency Impedance Plethysmograph and Adaptive Filtering", Rosell, Cohen & Webster, IEEE Transactions on Biomedical Engineering, Vol. 42, No. 10, October 1995, pages 1044-1048).

Other studies into multifrequency impedance monitoring have led to the finding that the amplitude of the transthoracic impedance (measured using a four-electrode system)  
10 decreases with frequency ("Multifrequency data collection and modelling of cardiac and respiratory related electrical impedance changes", Brown, Lu, Smallwood & Leathard, in Concerted Action on Electrical Impedance Tomography, Barcelona meeting, UPC, Barcelona 1993).

The present invention has resulted from studies carried out by the inventor to  
15 develop a method of ventilation monitoring less subject to movement artefact and therefore applicable in general patient monitoring, respiratory distress syndrome (RDS) and in sleep studies.

According to a first aspect of the invention, there is provided a method for monitoring respiratory condition by impedance pneumography comprising the steps of  
20 applying a first pair of spaced electrodes to a human body, applying a second pair of spaced electrodes for detecting a resulting electrical signal at different points on the body, applying an electrical signal to the first pair of electrodes at a plurality of frequencies, monitoring the resulting electrical signal at the second pair of electrodes at said plurality of frequencies, obtaining from the resulting electrical signal a measure of the impedance  
25 of a part of the body at the plurality of frequencies, obtaining a difference signal representing the impedance change with frequency, and dividing the difference signal by a signal representative of the impedance measure itself at one or more frequencies, thereby suppressing the effect of those impedance signal components whose frequency dependent change is substantially proportional to the impedance signal value.

30 The applied electrical signal is preferably a high frequency constant sinusoidal alternating current of an appropriate magnitude (eg. 100 $\mu$ A), whilst the monitored electrical

signal is preferably the real part of the resulting potential difference measured over the current path across the second pair of electrodes. As a constant drive current is employed, the impedance measure can be derived directly from the monitored potential difference.

The invention arises from observations by the inventor in electrical impedance tomography which have shown that for a region of interest over the lungs the absolute impedance changes during ventilation generally do not fall with frequency, whereas the impedances themselves do fall with frequency. If movement artefact is simply caused by changes in geometry then this should be represented by an artefact which is a constant fraction of the reference or 'baseline' impedance. It is therefore possible, by making use of the method of the invention, to separate ventilatory changes from movement changes.

The invention differs significantly from the known methods of impedance pneumography, which in no way consider normalising an impedance difference signal with respect to a signal representing the impedance itself.

The difference signal may be divided by a sum of the impedance measure at more than one frequency and this may be a weighted sum, the weighting selected according to appropriate criteria depending, for example, on a presupposed reliability of the measure at the different frequencies, and/or on knowledge of the way the electrical properties of lung tissue respond at different frequencies. For example, the weighting factors may all be zero except for that applied to the impedance measure at the lowest frequency. Preferably the frequencies are in the kHz range.

The signal obtained by the method described above may be low-pass filtered to remove or reduce, amongst other components, cardiac components which may produce unwanted artefact.

Alternatively or additionally, the signal may be band-pass filtered to remove or reduce the DC component of the signal.

In a preferred manner of carrying out the invention, the input electrodes may be situated on opposed sides, left and right, of the subject's trunk, whilst the output electrodes may be both placed on one side, preferably the right side, of the subject's trunk. If the output electrode pair is placed on the right side of the subject's trunk, the isolated electrode of the input pair is preferably located in the neighbourhood of the subject's left axilla.

According to a second aspect of the invention, there is provided an apparatus for

carrying out the above defined method, comprising a pair of spaced electrodes for applying an electrical signal to a human body and a pair of spaced electrodes for detecting a resulting electrical signal at different points on the body, a means for applying said signal to the first pair of electrodes at a plurality of frequencies, a means for monitoring the resulting  
5 electrical signal at the second pair of electrodes at said plurality of frequencies, a means for obtaining from the resulting electrical signal a measure of the impedance of a part of the body at the plurality of frequencies, a means for obtaining a difference signal representing the impedance change with frequency, and a means for dividing the difference signal by a signal representative of the impedance measure itself at one or more frequencies, such  
10 that the effect of those impedance signal components whose frequency change is substantially proportional to the impedance signal value can be suppressed.

The means for applying the electrical signal preferably comprises a signal generator capable of producing a plurality of high frequency constant alternating current signals, as well as two flexible leads for connection to the first pair of electrodes. The means for  
15 monitoring and/or the means for obtaining the impedance measure may comprise one or more adjustable gain voltage amplifiers, whilst the means for obtaining the difference signal and the means for dividing the difference signal by the signal representative of the impedance measure itself at the one or more frequencies preferably comprises a microprocessor, such as a PC, with a memory such that the signal may be sampled as  
20 appropriate and recorded for further processing. The apparatus may further include an output display and/or a printer. The microprocessor may include means for selective filtering of the signal, such as low-pass filtering means and means for dc rejection filtering after the low pass filter.

#### Electrode placing

25 The studies used a tetrapolar electrode arrangement, since such an arrangement minimises the effect of contact impedance changes on the impedance measured. It was necessary to devise an electrode placement which maximised the contribution of both lungs to the measurement, and this optimum placement was identified by inspecting all the data collected from a conventional 16 electrode EIT system and looking for the electrode  
30 combination which maximised the fractional impedance change during respiration. This

optimised electrode placement was found to be an isolated drive electrode at the left axilla, whilst the other drive electrode and the two receive electrodes were placed in close proximity to one another on the right side of the body, all three in approximately the same transverse plane at about the level of the 6th or 7th rib. The receive electrodes were spaced  
5 by about 5cm, whilst the second drive electrode was placed about 10cm further to the rear. Figure 1 depicts diagrammatically this arrangement. Clearly alternative electrode positions may be employed, such as those selected to target the impedance change originating in only the left or only the right lung. None of the electrodes need be arranged in a common transverse plane, and a 3-d arrangement may be used as required to highlight the impedance  
10 change associated with a particular target region. Additionally, the invention may be realised using more than four electrodes.

#### Experimental procedure

A signal generator capable of providing sinusoidally varying current of constant 1mA peak-to-peak amplitude simultaneously at different frequencies was used to supply  
15 the electrical signal to the drive electrodes. The drive signal was applied to normal male subjects at number of different frequencies, including 9.6 kHz, 38.4 kHz and 76.8 kHz, with the electrode placing specified above. Sample results are illustrated in Figures 2-5 and show the real part only of the impedance measured against time in seconds from the beginning of the respective test. The results were high-pass filtered to remove or at least  
20 reduce the cardiac signal.

In Figure 2, the transfer impedance in ohms at a frequency of 76.8 kHz is shown during various manoeuvres carried over a 90 second period. The “strong wriggling” consisted of twisting the trunk backwards, forwards and sideways as much as possible. During the initial period of breath-hold the subject also changed from sitting to a standing  
25 position and then back again. The breathing periods involved deep breathing, from maximum inspiration to maximum exhalation, and it can be seen that the changes in transfer impedance with breathing as a fraction of baseline (~ 45%) are very large. The “obstructive apnoea” period was simulated by applying a noseclip to the patient and having him close his mouth whilst still attempting to breathe using the muscles of the diaphragm  
30 and abdomen. The impedance changes here therefore represent respiratory effort rather

than ventilation.

In Figure 3 the same data is shown, but this time presented by reference to the 9.6 kHz data. The vertical scale therefore shows the (non-dimensional) fractional fall in impedance with frequency. The low frequency was chosen as the reference impedance because it is understood that low frequency impedance measurements are often the most accurate. The improvement in discrimination of ventilatory changes and movement changes is clear, particularly in the case of the significant change in impedance between sitting and standing, which discontinuity is largely suppressed by making use of the method of the invention.

Figures 4a-c show three traces recorded simultaneously from a measurement period consisting of various movements. The 'tidal breathing' referred to in these figures was ordinary, fairly shallow breathing, and the movement period involved strong wriggling by the subject. Figure 4a shows the trace from an airflow spirometer (a Gould water-sealed bell spirometer), whilst Figure 4b shows the impedance change data presented with reference to a 'baseline' impedance,  $(Z_{f3} - Z_{f1}) / (Z_{f3} + Z_{f1})$ . The 'baseline' impedance of  $(Z_{f3} + Z_{f1})$  was selected here to reference the impedance change over a broader frequency range than that used in the case of the results shown in Figure 3.  $f_1$  and  $f_3$  were, respectively, 9.6 kHz and 38.4 kHz. Figure 4c shows the transthoracic impedance, recorded as a bipolar impedance measurement between the two drive electrodes. Comparison of the traces clearly shows the significance of employing the method according to the invention, especially when compared with the simple bipolar pneumogram which gives very poor discrimination. Movement artefact is still evident in the trace of Figure 4b, but it is of considerably lower magnitude than respiratory changes. The normalisation of the results with reference to the sum of the impedance measures at two frequencies appears to give improved movement artefact suppression. It is also possible to normalise the results using a sum of the measures at more than two frequencies, or by making use of a weighted sum of impedance measures at the different frequencies, the weighting factors being selected according to presupposed characteristics. For example, the weighting may take into account the presupposed reliability of the measure at the different frequencies, or may be selected according to knowledge of the way lung tissue behaves at different frequencies.

Finally, Figures 5a to 5c show the traces of Figures 4a to 4c, but in this case all



three traces have been band-pass filtered from 0.125 to 2.5 Hz. This has the effect of removing the DC component of the signal. With such filtering, results from the conventional transthoracic impedance measurement (Figure 5c) shows some improvement, but it is clear that the trace resulting from the method of the invention (Figure 5b) provides  
5 a much clearer correlation with that derived from the airflow spirometer.

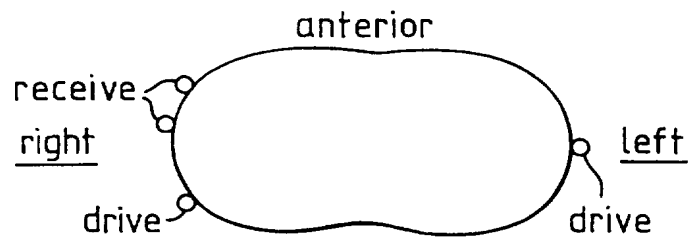
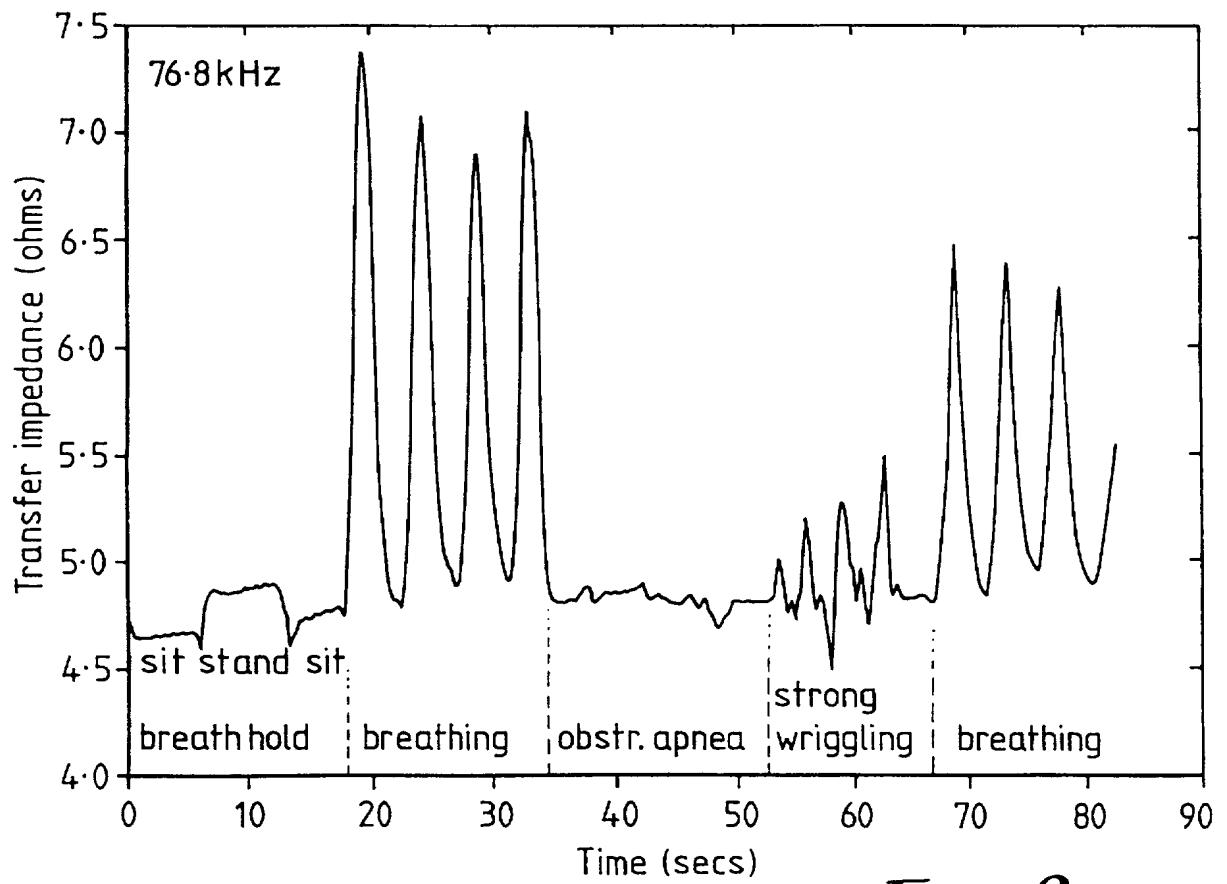
Embodiments of the invention described above are given by way of example only, and it should be understood that these in no way limit the invention which is intended to embrace all embodiments that fall within the scope of the appended claims.

## Claims

1. A method for monitoring respiratory condition by impedance pneumography, comprising the steps of applying a first pair of spaced electrodes to a human body, applying a second pair of spaced electrodes for detecting a resulting electrical signal at different points on the body, applying an electrical signal to the first pair of electrodes at a plurality of frequencies, monitoring the resulting electrical signal at the second pair of electrodes at said plurality of frequencies, obtaining from the resulting electrical signal a measure of the impedance of a part of the body at the plurality of frequencies, obtaining a difference signal representing the impedance change with frequency, and dividing the difference signal by a signal representative of the impedance measure itself at one or more frequencies, thereby suppressing the effect of those impedance signal components whose frequency dependent change is substantially proportional to the impedance signal value.
2. A method according to Claim 1, wherein the applied electrical signal is a high frequency constant sinusoidal alternating current.
3. A method according to Claim 1 or Claim 2, wherein the monitored electrical signal is the real part of the resulting potential difference measured over the current path across the second pair of electrodes.
4. A method according to any preceding claim 1, wherein the difference signal is divided by a sum of the impedance measures at more than one frequency.
5. A method according to Claim 4, wherein said sum of the impedance measures is a weighted sum.
6. A method according to Claim 5, wherein the weighting is selected according to a presupposed reliability of the measure at the different frequencies.
7. A method according to any preceding claim, wherein the plurality of frequencies are in the kHz range.
8. A method according to any preceding claim, wherein the resulting electrical signal is passed through a low-pass filter.
9. A method according to any preceding claim, wherein the resulting electrical signal is band-pass filtered to remove or reduce the DC component of the signal.
10. A method according to any preceding claim, wherein the input electrodes are

situated on opposed sides of the subject's trunk, whilst the output electrodes are both placed on one side of the subject's trunk.

11. An apparatus for monitoring respiratory condition by impedance pneumography, comprising a pair of spaced electrodes for applying an electrical signal to a human body and a pair of spaced electrodes for detecting a resulting electrical signal at different points on the body, a means for applying said signal to the first pair of electrodes at a plurality of frequencies, a means for monitoring the resulting electrical signal at the second pair of electrodes at said plurality of frequencies, a means for obtaining from the resulting electrical signal a measure of the impedance of a part of the body at the plurality of frequencies, a means for obtaining a difference signal representing the impedance change with frequency, and a means for dividing the difference signal by a signal representative of the impedance measure itself at one or more frequencies, such that the effect of those impedance signal components whose frequency change is substantially proportional to the impedance signal value can be suppressed.
12. An apparatus according to Claim 11, wherein the means for applying the electrical signal comprises a signal generator for producing simultaneously a plurality of high frequency constant alternating current signals, and connection means for supplying such signals to the first pair of electrodes.
13. An apparatus according to Claim 11 or Claim 12, wherein the means for monitoring the resulting electrical signal includes at least one adjustable gain voltage amplifier.
14. An apparatus according to any of Claims 11 to 13, wherein the means for obtaining the difference signal and the means for dividing the difference signal by the signal representative of the impedance measure itself at the one or more frequencies comprises a microprocessor computing means.
15. An apparatus according to Claim 14, wherein the microprocessor computing means includes means for low-pass filtering of the resulting electrical signal.
16. An apparatus according to Claim 14 or Claim 15, wherein the microprocessor means includes means for dc rejection filtering.

**Fig. 1****Fig. 2**

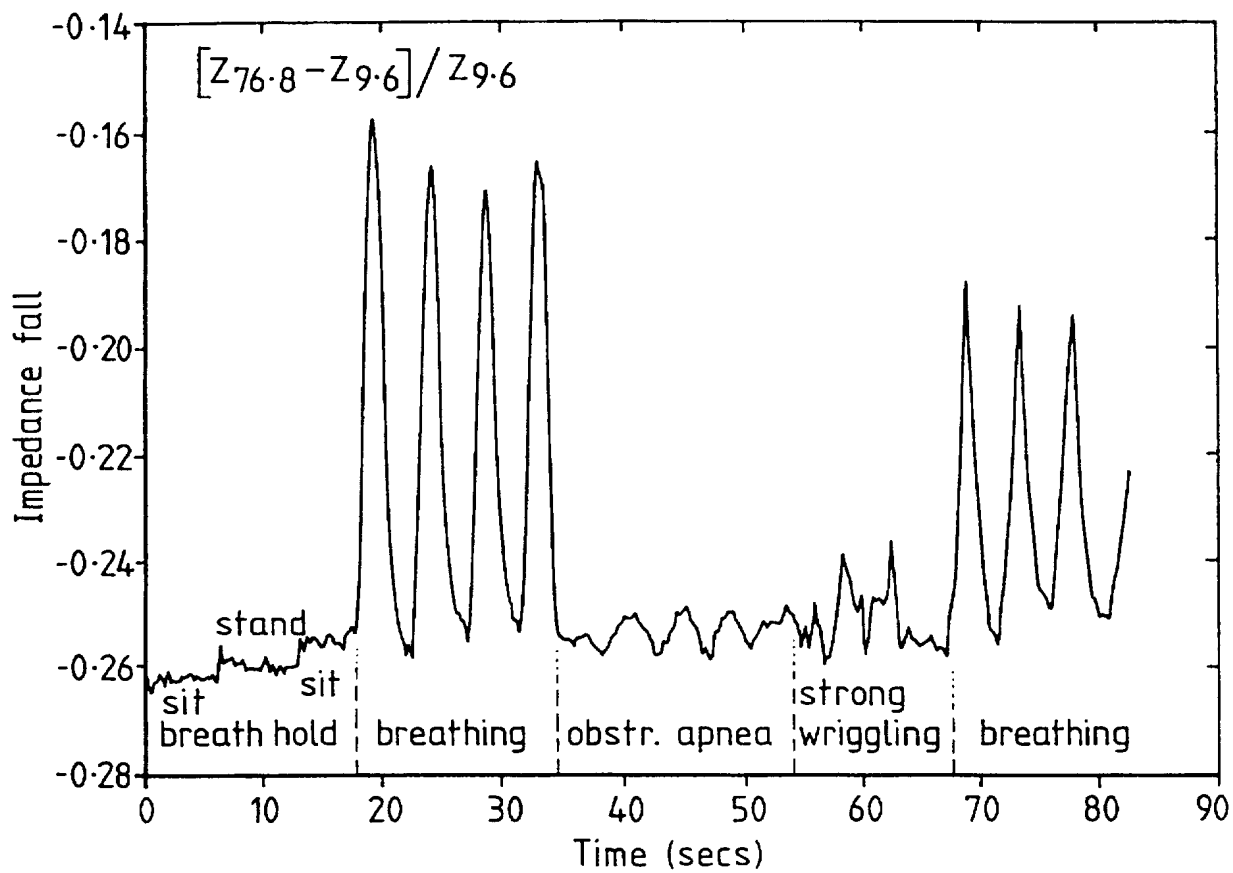


Fig. 3

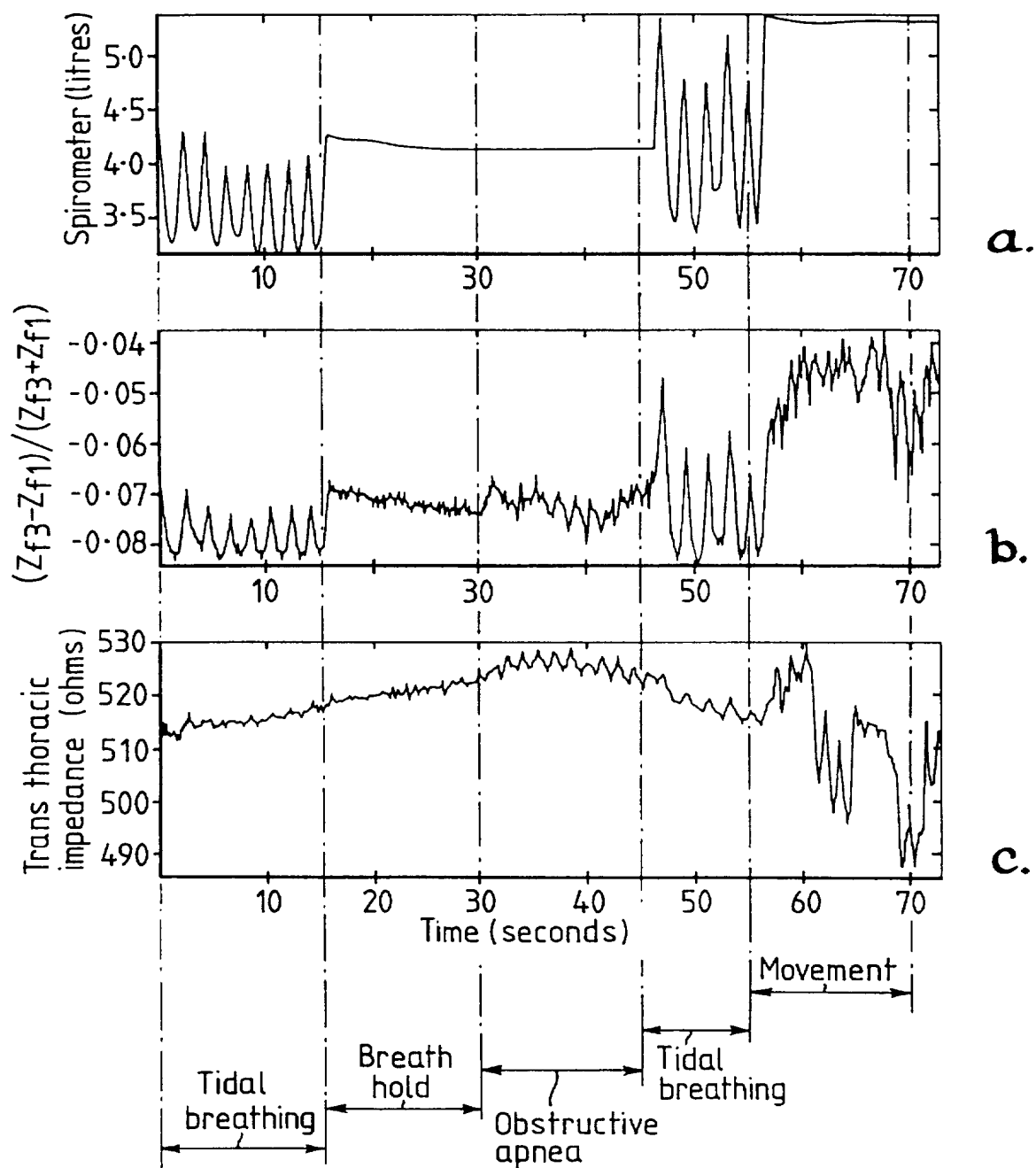


Fig. 4

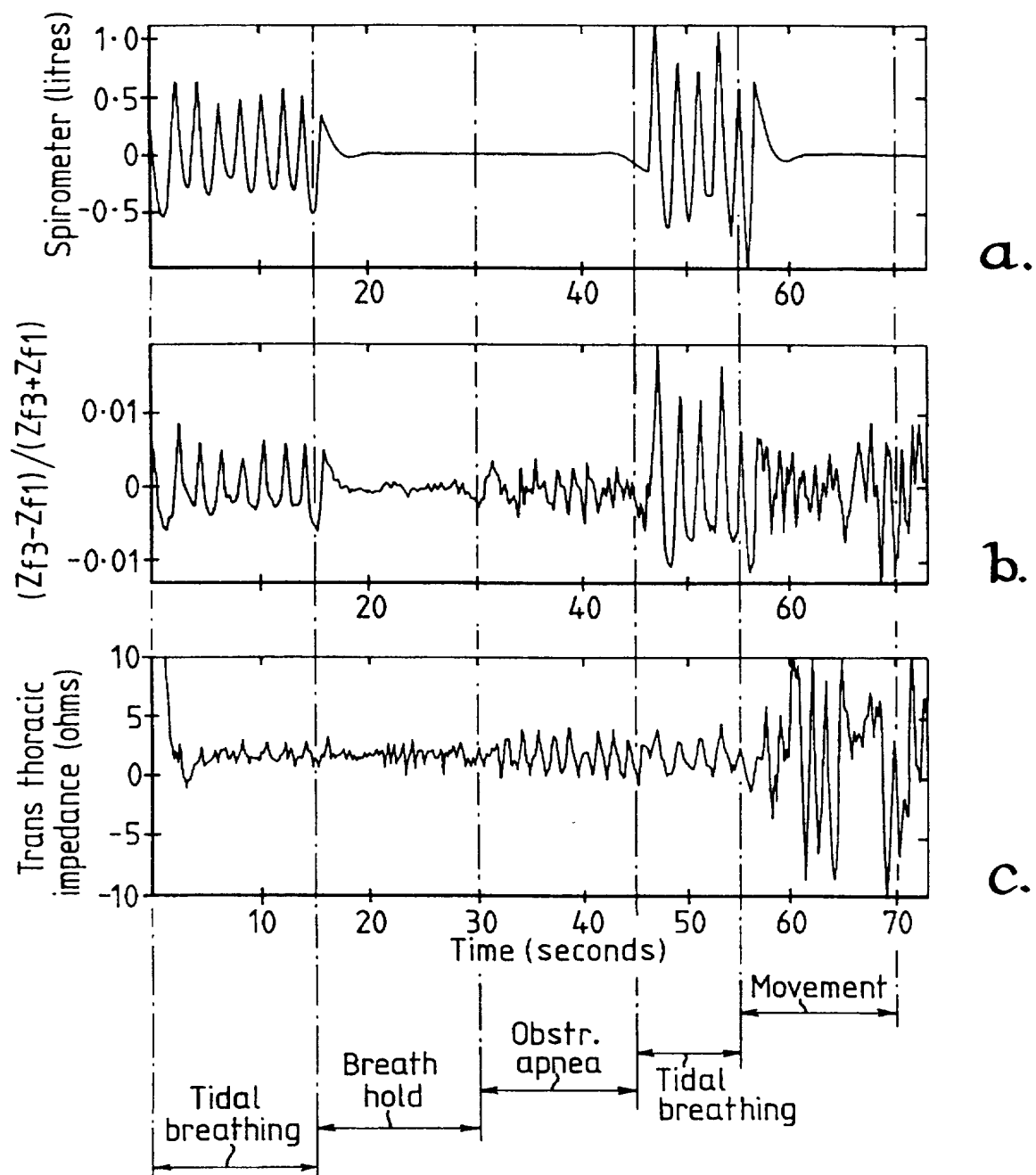


Fig. 5

# INTERNATIONAL SEARCH REPORT

International Application No  
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A. CLASSIFICATION OF SUBJECT MATTER  
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IPC 6 A61B

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## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category * | Citation of document, with indication, where appropriate, of the relevant passages  | Relevant to claim No. |
|------------|---|-----------------------|
| A          | <p>IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING,<br/>vol. 42, no. 10, October 1995, NEW YORK US,<br/>pages 1044-1048, XP000556838<br/>J. ROSELL ET AL.: "Reduction of Motion Artifacts Using a Two-Frequency Impedance Plethysmograph and Adaptive Filtering"<br/>cited in the application<br/>see the whole document</p> <p style="text-align: center;">---</p> <p style="text-align: center;">-/--</p> | 1,2,4,7               |

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Date of the actual completion of the international search

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| C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT |  |                       |
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Information on patent family members

International Application No

PCT/GB 96/03013

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